

# Dynamic brain networks measured by using phase synchronization across different seizure patterns

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## Background

- Typical recurrent waveforms (as in Fig. 1) often exist in seizure EEG signals.
- Such morphological EEG seizure patterns are related to clinical seizure types [1].
  - Fast spikes exist in most tonic seizures;
  - Spike-wave patterns occur during absence-like seizures, or at the end of tonic-clonic seizures;
  - Slow waves may present during focal seizures, and rhythmic delta/theta seizures;
  - Seizure-related EMG can exist in most tonic, tonic-clonic and myoclonic seizures.
- EEG seizure patterns may also correspond to different functional connectivity networks (FCNs) [2] of brain systems.

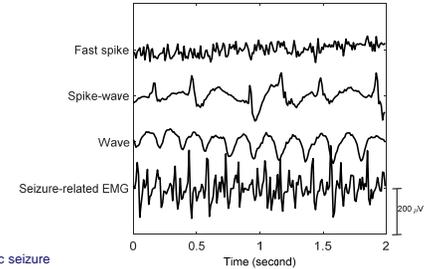


Figure 1. The four major EEG seizure patterns.

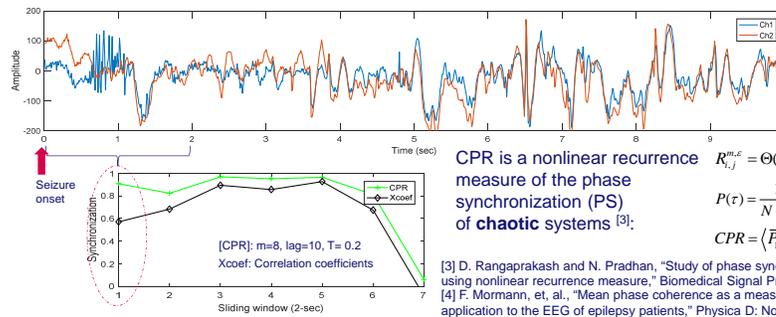
[1] R. Meier, et. al., "Detecting epileptic seizures in long-term human EEG: a new approach to automatic online and real-time detection and classification of polymorphic seizure patterns," J Clin Neurophysiol, vol. 25, no. 3, pp. 119-131, Jun 2008.

[2] S. P. Burns, et. al., "Network dynamics of the brain and influence of the epileptic seizure onset zone," Proceedings of the National Academy of Sciences, vol. 111, no. 49, 2014.

## Data & Methods

- Intellectual disability is one of the most common secondary disabilities in people with epilepsy.
- The 24-channel scalp EEG signals from 8 epilepsy patients with intellectual disability.
- EEG epochs of 24 seizure events (1414 seconds in total) and 1-min interictal EEG segments before each seizure onset were used in this study.

### Correlation between probabilities of recurrence (CPR):



CPR is a nonlinear recurrence measure of the phase synchronization (PS) of chaotic systems [3]:

### Phase lock index (PLI) [4]:

$$z(t) = s(t) + j\hat{s}(t) = A(t)e^{j\phi(t)}$$

$$\Delta\phi(t) = \phi_2(t) - \phi_1(t)$$

$$PLI = \left| \left\langle e^{j\Delta\phi(t)} \right\rangle \right|$$

$$R_{i,j}^{m,\epsilon} = \Theta(\epsilon - \|\bar{x}_i - \bar{x}_j\|)$$

$$P(\tau) = \frac{1}{N-\tau} \sum_{i=1}^{N-\tau} R_{i,i+\tau}^{m,\epsilon}$$

$$CPR = \left( \bar{P}_1(\tau) \bar{P}_2(\tau) \right) / (\sigma_1 \sigma_2)$$

[3] D. Rangaprakash and N. Pradhan, "Study of phase synchronization in multichannel seizure EEG using nonlinear recurrence measure," Biomedical Signal Processing and Control, vol. 11, 2014.  
[4] F. Mormann, et. al., "Mean phase coherence as a measure for phase synchronization and its application to the EEG of epilepsy patients," Physica D: Nonlinear Phenomena, vol. 144, 2000.

## Results & Conclusion

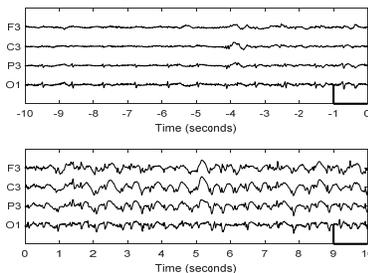


Figure 3a. The spike-wave seizure with seizure onset at 0 sec.

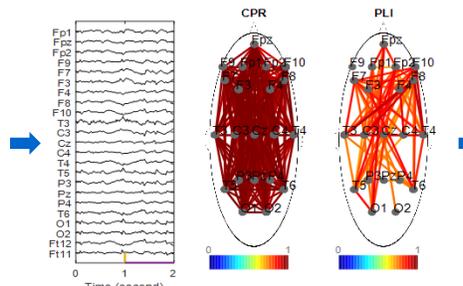


Figure 3b. The CPR and PLI-based FCNs (2-sec epoch).

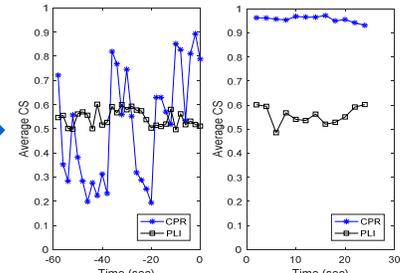


Figure 3c. Average connecting strength (CS) in each FCN based on CPR and PLI. (onset at 0 sec)

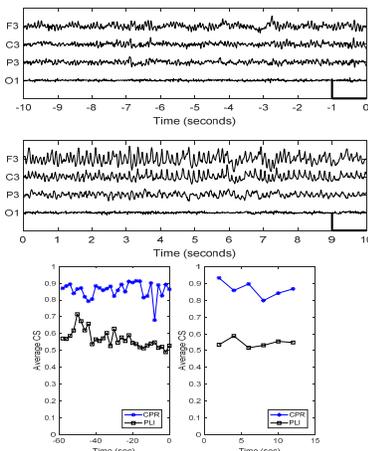


Figure 4. The wave seizure with seizure onset at 0 sec (above), and the average connecting strength (CS) in each FCN based on CPR and PLI. (onset at 0 sec) (down).

Table 1. Statistical results of average CS on the EEG epochs from 8 subjects.

Seizure pattern	No. of seizure events	Accumulated time (sec) of EEG epochs		t test of difference between sez and non-sez	
		Non-seizure (1 min before)	Seizure	CPR difference*	PLI difference*
A (spike)	8	480	88	-0.17	+0.09
B (spike-wave)	6	360	114	+0.14	#
C (wave)	6	360	747	+0.05	#
D (EMG)	4	240	465	-0.46	+0.16

\* denotes there is statistical difference between the non-seizure and seizure epochs in the column except that denoted by #. P value is smaller than 0.00001.

# denotes no statistical difference between the non-seizure and seizure epochs.

\*+/- denote normalized [-1 +1] increase/decrease from baseline (i.e., 1 min EEG before seizure).

Table 2. Statistical results agree with observations.

Seizure pattern	CPR (change after onset)	PLI (change after onset)
A (fast spike)	Decline (significantly) and return back	Increase
B (spike-wave)	Further increase (based on a high level)	No significant change
C (wave)	Increase slightly	No significant change
D (EMG)	Decline (significantly) and return back	Increase

**FCNs measured by using CPR outperform that by using PLI, and CPR-based FCNs show statistical difference before and during seizures in all seizure patterns.**